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A Study on the Effect of Cold Forming on the Yield Strength of Stainless Steel Type 304 - Hardness Test Approach

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A STUDY OF THE EFFECT OF COLD FORMING ON THE YIELD STRENGTH OF STAINLESS STEEL TYPE 304 - HARDNESS TEST APPROACH

by

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SYNOPSIS

This paper describes a preliminary experimental investigation of the effects of cold forming on the material properties of stainless steel corner sections. The background and theory behind the research is briefly reviewed and is followed by a description of hardness testing. Hardness testing is used to postulate values for the increase in yield strength around the corners. The experimental findings are presented and the postulated increases in yield strength are compared with those predicted by two existing theories, and by other experiments carried out by the authors. It is concluded that the linear relationships found between yield strength and hardness for some steels do not apply to the stainless steel investigated, and further research is required.

INTRODUCTION

The aim of this study is to investigate the applicability of hardness testing to determine the variation of material properties, in particular, yield strength of stainless steel corner sections of different thickness and radii of bend. It is postulated that the variation of yield strength around the corner and the average increase for a section can be found by carrying out a number of hardness tests on the area of the section and then converting these hardness values to yield strength. The results obtained in this way, when compared to existing design standards for cold-formed steel sections, and other experimental findings, can be used to ascertain the accuracy with which hardness testing can be used to describe the yield strength variation.

Cold-formed steel sections are commonly used in building structures, automobile body sections and domestic equipment and the main reasons for their proliferation are generally economic but also because of their ease of manufacture. The high strength to weight ratio means that structures made from cold-formed sections can be fabricated cheaply and easily. Almost any shape of section can be produced to a high degree of accuracy and in addition to this the cold forming process causes strain-hardening in most metals which increases the yield strength of the section.

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Cold-forming is essentially a bending operation which causes local strain-hardening around the corners of any bends made in the section. This creates a variation in the properties of the material throughout the cross-section because the effect of strain-hardening at the section corners gives them a higher yield and ultimate tensile strength when compared to the flat elements. This increase in strength can upgrade the load carrying capacity of the section and can be taken into account in the design process to further minimise the amount of material used.

STAINLESS STEELS

Design specifications for cold-formed mild steel sections have been in existence in many countries including the UK [1] and the USA [2] for many years. In the USA, several institutions have their own equivalent design codes for stainless steel, for example, AISI [3]. There is, however, no equivalent design code for cold-formed stainless steel sections in the UK.

Stainless Steels are steel alloys containing high quantities (at least 11%) of chromium. They generally contain low amounts of carbon and may also include other alloying elements such as nickel or molybdenum. Their main advantages over ordinary carbon steels are their greater strength and their high corrosion resistance (which is a result of the chromium oxide film which forms on the surface of the metal). They are, however, more difficult to machine and more expensive than mild steels to produce. Nevertheless they are extremely useful and more needs to be found out about their behaviour so that accurate design standards for stainless steel can be produced.

HARDNESS TESTING

Hardness testing is a non-destructive procedure used to measure the resistance of a material to plastic deformation. The most common type of test is the indentation test where an indenter is forced into the material under a specified load. The indentation left by the indenter can be measured and the hardness is given by the load divided by the surface area of the indentation. Hardness tests are performed more frequently than any other mechanical test because they are simple, inexpensive, and the results can be used to estimate other properties of the material - in particular the yield strength. Such predictions, however, only apply to materials for which these relationships have already been established. In the light of this hardness tests are most useful when considering the relative properties of similar materials or determining the uniformity of a batch of samples.

EXPERIMENTAL INVESTIGATION

In all, 32 different specimens were prepared and tested. These consisted of four different thicknesses of stainless steel, each bent into four different radii of bend and two different angles of bend - 45° (135°) and 90° to form short angle sections of length 50mm. A typical cross-section of a 90° angle is shown in Fig 1 and the leg length b is constant at 50mm. The specimens were bent using the bending rig shown in Fig 2, which was fabricated from steel bar and plate. The prepared specimens were then measured for actual thickness and radius of bend before being encased in blocks of epoxy resin to provide a stable base for the hardness tests.

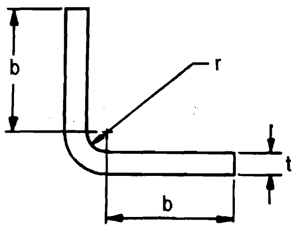


Fig 1 - Typical Specimen Cross-Section

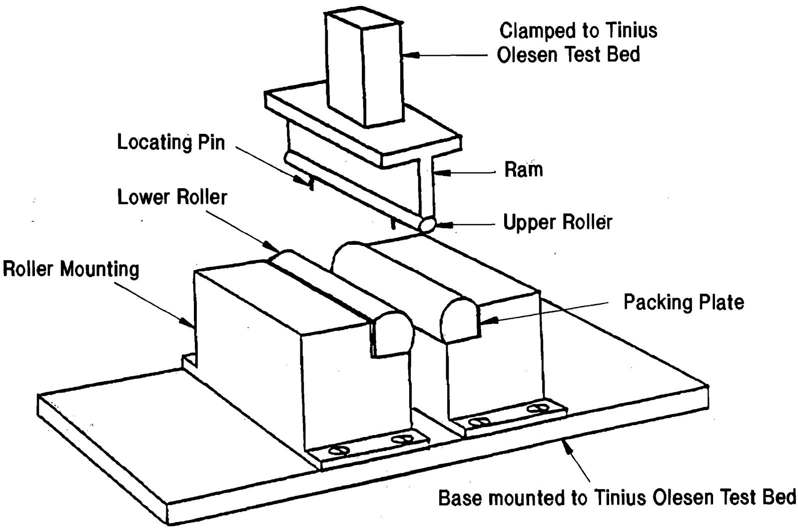
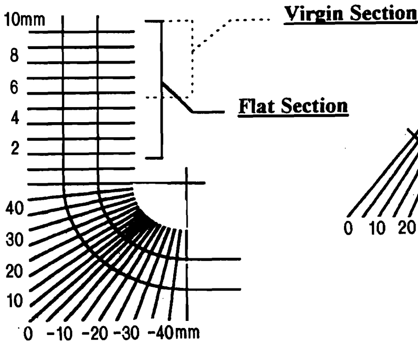


Fig 2 - Bending Rig

VICKERS HARDNESS TESTING

The Vickers Hardness test was used to determine the hardness values around the cold-formed section. A diamond pyramidal indenter is used thus removing the error introduced by deformation of the indenter. A relatively small load of 10kg was used so that the indentations were small enough for a number of tests to be carried out across the cross-section of the specimen. The location lines for the tests are shown Figs 3 and 4:-



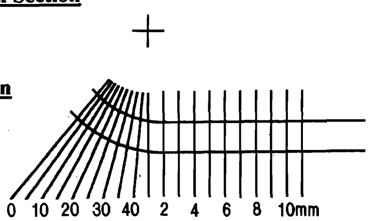


Fig 3 - 90° Bend Specimen

Fig 4 - 45° Bend Specimen

For the 3mm specimens 6 tests were carried out on each location line across the section thickness; 4 for the 2mm thickness and only 1 for the 0.9 and 0.7mm thickness specimens. The average diagonal lengths of the indentations were measured using the microscope of the hardness testing machine and then converted to hardness values using standard tables.

ESTIMATING YIELD STRENGTH FROM HARDNESS NUMBER

Hardness values alone are of very little use structurally. However, the possibility of the existence of a relationship between yield strength and hardness can make them extremely useful. Tabor [4] theorised that the two properties are related linearly and derived simple equations for a number of metals. Unfortunately, these did not prove accurate for stainless steel - possibly because of work hardening occurring during the hardness tests. Therefore a relationship had to be derived empirically in this research between the Vickers hardness number and the yield strength for the stainless steel under investigation. Many publications, including Tabor, on the correlation of hardness to yield strength for mild steel state that the hardness number divided by 3 gives a good prediction of yield for virgin material. A series of tensile tests and Vickers hardness tests was carried on specimens of the various thicknesses of virgin material. From these tests it was found that a factor of approximately 6.7 gave a consistently good correlation between hardness and yield for the virgin material. This factor was thereafter used for conversion of the hardness results to yield strength values for the cold-formed corner sections, and from the hardness tests postulations of the variation of yield strength around the corners and through the thickness could be made.

Using these results, 3D hardness plots and average values of the yield strength of the sections were obtained. The increase in yield strength around the corner was obtained by comparing the average for the corner with the average yield strength of the first 5mm section of the flat element (which showed no work hardening).

RESULTS AND OBSERVATIONS

HARDNESS AND YIELD STRENGTH VARIATIONS

The 3-D plot shown in Fig 5 gives a graphical picture of the variation of hardness around the corner section for one of the tests. Note that in this figure, and succeeding figures, the factor of 6.7 has been used to convert hardness numbers to yield strengths. The factor is used as in the following expression:-

$$F_y = \frac{9.81 \times H_v}{6.7}$$

From Fig 5 it is easy to see which areas are most affected by strain hardening. The highest strengths are found midway around the bend (the 0 degree line on Figs 3 and 4) at the inner and outer edges where there has been the greatest amount of tension or compression. The peak values of these were found to be up to 1.4 times the strength of the virgin metal. However, moving from the edges to the middle of the specimen the yield strengths were noticeably less but still showed some increase from the virgin metal. Theoretically there should be a "neutral axis" where no strain hardening occurs. This may exist but could not be detected. Fig 6 shows the average of the yield stresses on each location line. This shows how the yield strength values drop away quickly towards the ends of the arc of the bend and almost no increase in yield strength was noticeable more than 2 or 3mm from the limit of the bent section as can be seen from Fig 7. The effects of cold forming can be considered to be limited almost completely to the arc of the bend.

POSTULATED INCREASES IN YIELD STRENGTH

The average yield strength of all the points on the corner section was used to calculate the overall increase in yield strength of the section. The results for all the specimens are given in Tables 1 and 2. The maximum overall increase measured was 17% greater than the virgin metal. The was for the 3mm thick specimen bent to a 90° corner with the tightest radius of bends.

EFFECT OF SPECIMEN THICKNESS

There was a marked difference between the amount of strain hardening in the different thicknesses of specimen. The thicker the specimen the greater the

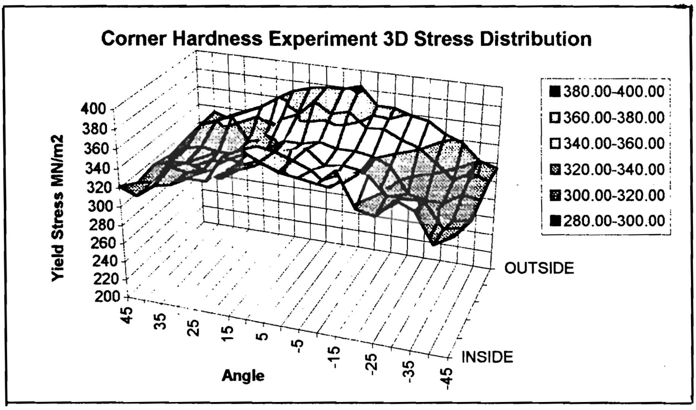


Fig 5 - 90° Bend: t = 3.34mm, r = 7.5mm

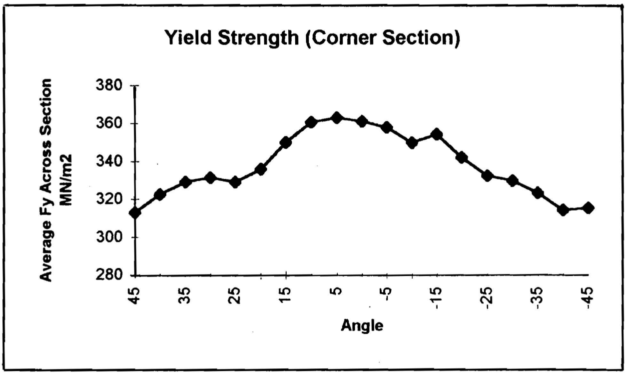


Fig 6 - Average F_Y Across Location Line (Corner Section)

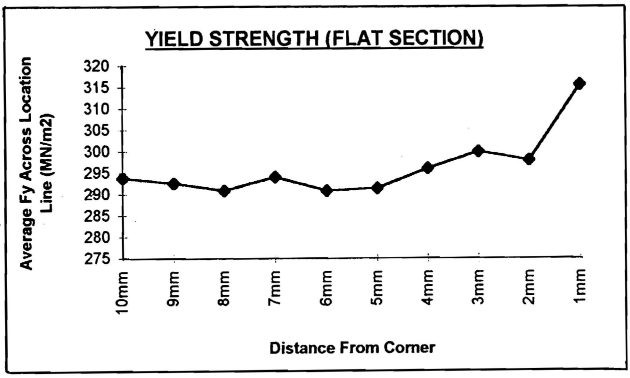


Fig 7 - Average F_Y Across Location Line (Flat Section) amount of work hardening observed. This is because the material towards the edges of the thicker specimens has to be deformed further to form the radius of bend and so is strain hardened to a greater extent. This was noted for both 90° and 45° bends, but was much clearer for the 90° bend.

EFFECT OF RADIUS OF BEND

The effects of the different corner radii was not as pronounced as the thickness effect, but in general the tightest bends for each thickness exhibited the greatest increases in yield strength. This was as would be expected from theory since the smaller radii of bend cause more local deformation.

EFFECT OF ANGLE OF BEND ON STRAIN HARDENING

Comparison of the results for the 45° and 90° specimens, as expected, showed a greater degree of work hardening for the 90° specimens. These displayed increases in yield which were generally more than twice that of those found in the 45° specimens. This showed quite clearly the effect of the amount of cold-working on the increase in yield strength of the specimen.

COMPARISON OF EXPERIMENTAL RESULTS AND DESIGN CODES

There are two existing design methods for predicting the strength increase in corner sections due to cold-forming. The first is set down in BS 5950 Part 5 [2] (which deals with mild steels and is not applicable to stainless). The second is an adaptation for stainless steel Type 304 by Van Den Berg [5] of the American Iron and Steel Institute specification [4]. The experimental results were very much lower than those predicted by both theories. The BS equation in particular gave very high results. This is understandable when considering that the BS is not intended for use with stainless steel. However, the poor correlation between the results from the hardness test approach and both design approaches causes much doubt as to the validity of this approach for stainless steel. In addition to this, a parallel investigation using a purely tensile test approach, as reported by Fenwick [6], showed much larger increases in yield strength. This suggests that the hardness test approach may not be reliable for measuring the yield strength of metals which work harden appreciably. However this approach does indicate the trends and provide a means whereby a pictorial mapping of variation of hardness and yield in the vicinity of cold formed corners can be obtained. These effectively highlight the areas of greatest work hardening.

CONCLUSIONS

The results of this research were fairly mixed. They were quite effective in mapping the concentration of hardness and yield strength around the corner section and showing which areas were subjected to the greatest amount of strain-hardening during the bending process. They also identified the factors which affected the increase in yield strength - specifically the bend radius and thickness and the amount of cold forming. Quantitatively, however, the results were not as good as was initially hoped. The increases in yield strength measured were significantly smaller than either the design code predictions and the results of the tensile tests carried out.

The reason for this lies in the relationships between hardness and yield strength used in the calculations. The Tabor equations relating hardness to yield strength gave poor results using the factor of 6.7, which was derived empirically on the basis that it gave a good correlation between the virgin hardness and tensile test results. This good correlation obviously does not extend to the strain hardening zone. Also the assumption that the relationship between the two properties is a linear one cannot be taken for granted for materials which work harden or even for areas of the same specimen which have been subjected to different degrees of work hardening.

The experimental results do not provide a particularly accurate correlation with design codes, but they do at the very least produce a detailed map showing the trends of yield strength concentrations around cold-formed stainless steel corner sections. As the results stand they do not seem accurate enough to be able to recommend hardness testing as a valid alternative to the more expensive tensile testing method. More needs to be known about the relationship between hardness and yield strength for cold-formed stainless steel before the results can be used with confidence.

REFERENCES

1 **AISI, Specification for the Design of Cold Formed Steel Structural Members.** 1986.

2 **BS 5950 Part 5: 1990, Design of Cold-Former Steel Members.**

3 **AISI, Specification for the Design of Light Gage Cold-Formed Stainless Steel Structural Members.** 1989.

4 Tabor, D., **The Hardness of Metals,** Oxford University Press, 1951.

5 Van Den Berg, G.J. and Van Der Merwe, P., **Prediction of Corner Mechanical Properties for Stainless Steels Due to Cold Forming,** Paper Presented at the 11th Specialty Conference on Cold Formed Steel Structures, St. Louis, USA. October 1992.

6 Fenwick, S.T., **A Study of The Effects of Cold-Forming on the Yield Strength of Stainless Steel Type 304,** BEng (Hons) Mechanical Engineering Thesis, Strathclyde University, 1996.

90 Degree Bend Specimens											
Specimen No	Thickness (mm)	Inside Radius (mm)	Expt Average Corner Yield Strength	Expt Virgin Fy	Virgin (0.2%) Fy From Tensile Test	Virgin UTS From Tensile Test	BS 5950 Fy	Van Den Berg Fy	Expt % Increase In Yield Strength	BS 5950 % Increse In Yield Strength	Van Den Berg % Increase In Yield Strength
S 1-1	0.67	3.9	300.31	281.42	290	690	491.54	344.43	6.71	69.50	18.77
S 1-2	0.67	4.9	316.28	293.13	290	690	453.04	331.04	7.89	56.22	14.15
S 1-3	0.67	6.2	289.21	293.13	290	690	420.60	317.77	-1.34	45.04	9.58
S 1-4	0.67	7.5	435.32	293.13	290	690	398.93	307.43	48.51	37.56	6.01
S 2-1	0.86	5.4	308.56	288.74	285	681	471.04	331.97	6.86	65.28	16.48
S 2-2	0.86	5.5	304.16	292.25	285	681	467.90	330.91	4.08	64.17	16.11
S 2-3	0.86	6	300.77	288.74	285	681	453.68	325.93	4.17	59.18	14.36
S 2-4	0.86	7.5	299.08	287.56	285	681	421.77	313.49	4.00	47.99	10.00
S 3-1	1.98	5.6	321.87	297.37	300	683	666.48	425.11	8.24	122.16	41.70
S 3-2	1.99	5.9	318.77	295.03	300	683	652.04	421.77	8.04	117.35	40.59
S 3-3	1.97	6	322.76	299.79	300	683	644.01	419.87	7.66	114.67	39.96
S 3-4	1.98	7.5	318.42	295.25	300	683	584.46	404.80	7.85	94.82	34.93
S 4-1	3.34	5.5	344.96	293.86	288	669	853.23	438.01	17.39	196.26	52.09
S 4-2	3.39	5.9	339.88	294.69	288	669	829.59	433.90	15.34	188.05	50.66
S 4-3	3.37	6.7	339.88	294.06	288	669	775.67	424.17	15.58	169.33	47.28
S 4-4	3.37	7.5	337.69	292.45	288	669	733.19	416.10	15.47	154.58	44.48

Table 1 - Theoretical and Experimental Results: 90° Bend Specimens

45 Degree Bend Specimens											
Specimen No	Thickness (mm)	Inside Radius (mm)	Expt Average Corner Yield Strength	Expt Virgin Fy	Virgin (2%) Fy From Tensile Test	Virgin UTS From Tensile Test	BS 5950 Fy	Van Den Berg Fy	Expt % Increase In Yield Strength	BS 5950 % Increase In Yield Strength	Van Den Berg % Increase In Yield Strength
S 1-5	0.67	9.8	298.25	290.49	290	690	364.42	287.04	2.67	29.04	1.20
S 1-6	0.68	11.3	299.13	290.79	290	690	374.21	293.47	2.87	25.66	-1.02
S 1-7	0.67	13.2	299.13	287.56	290	690	353.06	278.67	4.02	21.74	-3.91
S 1-8	0.67	15.7	296.20	288.44	290	690	343.23	270.40	2.69	18.35	-6.76
S 2-5	0.86	13.2	306.45	295.47	285	681	364.57	284.06	3.72	27.92	-0.33
S 2-6	0.87	13.3	307.62	294.89	285	681	364.88	284.26	4.32	28.03	-0.26
S 2-7	0.86	14.1	307.33	296.64	285	681	359.64	280.82	3.60	26.19	-1.47
S 2-8	0.85	15.7	298.25	290.20	285	681	351.48	275.04	2.77	23.33	-3.49
S 3-5	1.99	11.3	308.21	298.77	300	683	497.42	378.24	3.16	65.81	26.08
S 3-6	1.98	14	307.51	297.67	300	683	460.05	364.16	3.31	53.35	21.39
S 3-7	1.98	14.1	307.62	299.06	300	683	461.11	364.59	2.86	53.70	21.53
S 3-8	1.98	19.5	303.71	297.23	300	683	417.87	344.90	2.18	39.29	14.97
S 4-5	3.38	14	312.02	297.18	288	669	549.39	374.31	4.99	90.76	29.97
S 4-6	3.37	15.6	308.06	297.57	288	669	524.57	367.29	3.53	82.14	27.53
S 4-7	3.36	19.5	306.67	296.01	288	669	480.49	353.41	3.60	66.84	22.71
S 4-8	3.37	20.5	305.04	295.52	288	669	472.32	350.59	3.22	64.00	21.73

Table 2 - Theoretical and Experimental Results: 45° Bend Specimens

Note : - All Yield Strengths in MN/m^2